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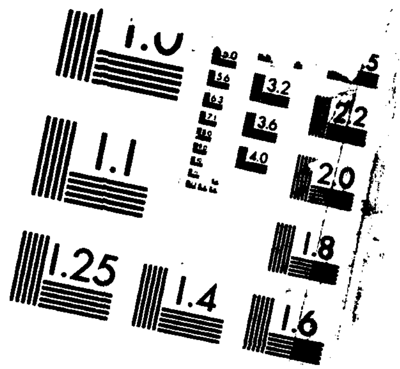

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A Compilation of Field Strength Formulas for ELF Radio Wave Propagation in the Earth-Ionosphere Waveguide

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Preface

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This report presents new formulas for ELF electric and magnetic dipole propagation in the earth-ionosphere waveguide. These new formulas extend the Wait and Galejs results, which are valid for distances greater than approximately three ionospheric reflecting heights, down to the quasi-nearfield range. Simplified versions of these general formulas that are valid for four specific ranges are also presented.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

a	Radius of the earth (~ 6.37 megameters)
c	Velocity of light in free space (~ 3×10^8 meters per second)
c/v	Earth-ionosphere waveguide phase-velocity ratio
ELF	Extremely low frequency (30 to 300 Hz)
E_ρ	Horizontal electric-field component in the ρ direction (volts/meter)
E_ϕ	Horizontal electric-field component in the ϕ direction (volts/meter)
E_z	Vertical electric-field component (volts/meter)
f(x)	$1 - xH_0^{(2)}(x)/H_1^{(2)}(x)$
G(u)	$\left(\frac{2u}{\pi}\right)\coth u + \left(1 - \frac{2}{\pi}\right)u^2 \operatorname{csch}^2 u$
G(t)	$\left(\frac{2t}{\pi}\right)\coth t + \left(1 - \frac{2}{\pi}\right)t^2 \operatorname{csch}^2 t$
h	Ionospheric reflection height (meters)
$H_0^{(2)}(x)$	Hankel function of the second kind, order zero, and argument x
$H_1^{(2)}(x)$	Hankel function of the second kind, order one, and argument x
HED	Horizontal electric dipole
HMD	Horizontal magnetic dipole
H_ρ	Horizontal magnetic-field component in the ρ direction (amperes/meter)
H_ϕ	Horizontal magnetic-field component in the ϕ direction (amperes/meter)
H(t)	G(t) + V(t)
I	Current (amperes)
k	$2\pi/\lambda_0$ (meters^{-1})
m	Magnetic dipole moment (ampere meters^2)
MKS	Meter-kilogram-second

NUSC	Naval Underwater Systems Center
p	Electric dipole moment (ampere meters)
S	$\sqrt{\dfrac{\rho/a}{\sin(\rho/a)}}$, spherical earth spreading factor
ikS_0	ELF earth-ionosphere waveguide propagation constant
t	$\dfrac{u}{(c/v)^2} = \dfrac{\pi\rho}{2h(c/v)^2}$
T	$\dfrac{G(u)e^{-\alpha\rho}}{ik\rho}\left(\dfrac{-i\pi x}{2}\right)H_1^{(2)}(x)$
u	$\dfrac{\pi\rho}{2h}$
v	Earth-ionosphere waveguide propagation velocity (meters/second)
VED	Vertical electric dipole
W	$\dfrac{e^{-\alpha\rho}}{(k\rho)^2}\left[V(t) + \dfrac{i\pi}{2}G(u)x^2H_0^{(2)}(x)\right]$
x	$k\rho(c/v)$
z	Vertical distance in a cylindrical coordinate system (meters)
α	Earth-ionosphere waveguide attenuation rate (nepers/meter)
γ_0	ik, free-space propagation constant (meters^{-1})
γ_e	$[i\omega\mu_0(\sigma_e + i\omega\varepsilon_e)]^{1/2}$, propagation constant in the earth (meters^{-1})
γ_i	$[i\omega\mu_0(\sigma_i + i\omega\varepsilon_i)]^{1/2}$, propagation constant in the ionosphere (meters^{-1})
ε_0	$10^{-9}/36\pi$ farads/meter, permittivity of free space
ε_e	Effective permittivity of the earth (farads/meter)
ε_i	Effective permittivity of the ionosphere (farads/meter)
η_0	120π, impedance of free space (ohms)
η_e	$\sqrt{\dfrac{i\omega\mu_0}{\sigma_e + i\omega\varepsilon_e}}$, impedance of the earth (ohms)
λ_0	Free-space wavelength (meters)
λ_e	Wavelength in the earth (meters)

μ_0	$= 4\pi \times 10^{-7}$ henries/meter, permeability of free space
ρ	Radial distance in a cylindrical coordinate system (meters)
ρ_{mv}	Distance where the minimum value of the VED radial wave impedance occurs (kilometers)
σ_e	Effective conductivity of the earth (Siemens/meter)
σ_i	Effective conductivity of the ionosphere (Siemens/meter)
ϕ	Azimuth angle in a cylindrical coordinate system
ω	$2\pi f$ radians/second, angular frequency

A COMPILATION OF FIELD-STRENGTH FORMULAS FOR ELF RADIO-WAVE PROPAGATION IN THE EARTH-IONOSPHERE WAVEGUIDE

INTRODUCTION

It is the purpose of this report to present new formulas for horizontal electric dipole (HED), horizontal magnetic dipole (HMD), and vertical electric dipole (VED) extremely low frequency (ELF) radio-wave propagation in the earth-ionosphere waveguide. These new formulas extend the results of Wait[1] and Galejs,[2] which are valid for measurement distances, ρ, greater than approximately three ionospheric reflecting heights, h, down to the quasi-nearfield range, which is defined as the range where ρ is greater than an earth wavelength, λ_e, but much less than a free-space wavelength, λ_0. For the sake of completeness, the abovementioned previously derived formulas also will be included.

The three dipole antennas (VED, HED, and HMD) are situated at zero height with respect to a cylindrical coordinate system (ρ,ϕ,z) and are assumed to carry a constant current, I. The axes of the VED and HED (of dipole moment p) are oriented in the z and x directions, respectively, while the axis of the HMD (of dipole moment m) is oriented in the y direction. The ionosphere is located at height $z \geq h$, while the earth is located at height $z \leq 0$. The propagation constant in the air is denoted by

$$\gamma_0 \; [= ik = i2\pi/\lambda_0] \; ,$$

whereas the propagation constants in the earth and ionosphere are denoted by

$$\gamma_e \left[= \sqrt{i\omega\mu_0(\sigma_e + i\omega\varepsilon_e)} \right]$$

and

$$\gamma_i \left[= \sqrt{i\omega\mu_0(\sigma_i + i\omega\varepsilon_i)} \right] \; ,$$

respectively. The magnetic permeability of the whole space is assumed to equal μ_0, the permeability of free space. Meter-kilogram-second (MKS) units are employed and a suppressed time factor of $\exp(i\omega t)$ is assumed.

DERIVATION PROCEDURE

Accounting for ionospheric reflection effects out to distances of approximately three ionospheric reflecting heights, h, is a tedious process involving an infinite sum of images.[1-3] However, by following the procedure outlined by Martin[3] and Bannister and Williams,[4] we find that each VED, HED, and HMD field-component expression can be multiplied by one of the following four functions:

$$G(u) = \left(\frac{2u}{\pi}\right)\coth u + \left(1 - \frac{2}{\pi}\right)u^2 \operatorname{csch}^2 u \tag{1}$$

$$G(t) = \left(\frac{2t}{\pi}\right)\coth t + \left(1 - \frac{2}{\pi}\right)t^2 \operatorname{csch}^2 t \tag{2}$$

$$V(t) = t^3 \coth t \operatorname{csch}^2 t \tag{3}$$

and

$$H(t) = G(t) + V(t) \ , \tag{4}$$

where

$$u = \frac{\pi\rho}{2h} \tag{5}$$

and

$$t = \frac{u}{(c/v)^2} \ , \tag{6}$$

where c/v is the earth-ionosphere waveguide phase-velocity ratio

$$c \approx 3 \times 10^8 \text{ m/s} \ .$$

The functions G(t), H(t), and V(t) are plotted versus t in figure 1.* Note that the plot of G(t) versus t is also a plot of G(u) versus u. When $u < 0.5$, $G(u) \approx 1$; when $t < 0.5$, $G(t) \approx V(t) \approx 1$. However, when $t < 2$, $H(t) \approx 2$. Furthermore, when $u > 2.5$, $G(u) \approx 2u/\pi$; when $t > 2.5$, $G(t) \approx 2t/\pi$. However, when $t > 4.5$, $V(t) \approx 0$ and $H(t) \approx 2t/\pi$.

When the measurement distance, ρ, is greater than approximately three ionospheric reflecting heights from the source, each VED, HED, and HMD field-component expression varies as a Hankel function,

$$H_0^{(2)}(kS_0\rho)$$

or

$$H_1^{(2)}(kS_0\rho)$$

(or a combination of the two), where $k = 2\pi/\lambda_0$ and ikS_0 is the propagation constant in the earth-ionosphere waveguide. S_0 is related to the phase velocity v and attenuation rate α by the formulas $c/v = \mathrm{Re}S_0$ and $\alpha = -8.7k\ \mathrm{Im}S_0$.

At ELF (i.e., 30 to 300 Hz), $\mathrm{Re}(kS_0\rho) \gg \mathrm{Im}(kS_0\rho)$. Therefore,

$$H_0^{(2)}(kS_0\rho) \approx H_0^{(2)}(x)e^{-\alpha\rho} \tag{7}$$

---

*All figures have been placed together at the end of this report.

and

$$H_1^{(2)}(kS_0\rho) \sim H_1^{(2)}(x)e^{-\alpha\rho} \ , \tag{8}$$

where

$$x = k\rho(c/v) \ . \tag{9}$$

In this report, we will use previously derived[5-8] quasi-nearfield range formulas ($\rho > \lambda_e$, $\rho << \lambda_0$, and $\rho < h/3$), as well as the Wait[1] and Galejs[2] formulas ($\rho > 3h$), to find VED, HED, and HMD formulas valid at ELF for $\rho > \lambda_e$ with no restrictions on the ratio of ρ to h.

As an example of our derivation procedure, consider the VED H_ϕ component. When $\rho > 3h$,

$$H_\phi^{VE} \sim \frac{ipk(c/v)}{4h} H_1^{(2)}(x)e^{-\alpha\rho} = \frac{pe^{-\alpha\rho}}{2\pi\rho^2}\left(\frac{\rho}{h}\right)\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x) \ . \tag{10}$$

For $x \leq 0.25$, equation (10) reduces to

$$H_\phi^{VE} \sim \frac{p}{2\pi\rho^2}\left(\frac{\rho}{h}\right) . \tag{11}$$

When $\rho < h/3$, the quasi-nearfield range formula is

$$H_\phi^{VE} \sim \frac{p}{2\pi\rho^2} . \tag{12}$$

Since $G(u) \sim 1$ for $\rho < h/3$ and ρ/h for $\rho > 3h$, then, for $x \leq 0.25$,

$$H_\phi^{VE} \sim \frac{pG(u)}{2\pi\rho^2} . \tag{13}$$

Because the range of validity of equations (10) and (13) overlap when $\rho > 3h$ and $x \leq 0.25$, we can substitute G(u) for ρ/h in equation (10) to obtain the general formula valid for $\rho > \lambda_e$ (with no restrictions on the ratio of ρ to h). It is

$$H_\phi^{VE} \sim \frac{pG(u)e^{-\alpha\rho}}{2\pi\rho^2}\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x) \ . \tag{14}$$

Wait's expression[1] for H_ϕ^{VE} is

$$H_\phi^{VE} \sim \frac{ik\,pT}{2\pi\rho} . \tag{15}$$

Therefore,

$$T \sim \frac{G(u)e^{-\alpha\rho}}{ik\rho}\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{16}$$

which, for $x \leq 0.25$, reduces to

$$T \sim \frac{G(u)}{ik\rho} \tag{17}$$

The magnitude of T (from equation (16)) is compared with Wait's infinite sum-of-images result[1] in figure 2 as a function of distance and frequency. For this particular comparison, h = 90 km and $\sigma_i = \infty$ (i.e., c/v = 1.0 and $\alpha = 0.0$). Note that the agreement is excellent.

We know from previous results[1,2] that there is a substantial amplitude dip in the VED E_z component in the range of 100 to 300 km (depending on frequency). Therefore, we will let

$$E_z^{VE} = E_{z1} - E_{z2} \; . \tag{18}$$

For $\rho < h/3$, the quasi-nearfield range formula is

$$E_{z1} \sim \frac{ip}{2\pi\omega\varepsilon_0\rho^3} = \frac{i60p}{k\rho^3} \; . \tag{19}$$

For ρ comparable to h, we can easily show that

$$E_{z1} \sim \frac{i60pV(t)}{k\rho^3} \; , \tag{20}$$

which reduces to equation (19) when t < 0.5 and vanishes when t > 4.5.

When ρ > 3h,

$$E_{z2} \sim \frac{30\pi pk}{h}(c/v)^2 H_0^{(2)}(x)e^{-\alpha\rho} = \frac{i60p}{k\rho^3}\left[-iux^2 H_0^{(2)}(x)e^{-\alpha\rho}\right] \; . \tag{21}$$

[illegible] .25, equation (21) reduces to

$$E_{z2} \sim \frac{i60p}{k\rho^3}\left[\left(\frac{2u}{\pi}\right) x^2 \left\{\ell n\left(\frac{1.123}{x}\right) \frac{i\pi}{2}\right\}\right] \Rightarrow \frac{i60pG(u)x^2}{k\rho^3}\left\{\ell n\left(\frac{1.123}{x}\right) - \frac{i\pi}{2}\right\} \; . \tag{22}$$

Therefore,

$$E_{z2} \sim \frac{i60pe^{-\alpha\rho}}{k\rho^3}\left[\left(\frac{-i\pi}{2}\right)G(u)x^2 H_0^{(2)}(x)\right] \; . \tag{23}$$

Employing equations (18), (20), and (23) results in

$$E_z^{VE} \sim \frac{i60pe^{-\alpha\rho}}{k\rho^3}\left[V(t) + \frac{i\pi}{2}G(u)x^2 H_0^{(2)}(x)\right] \; , \tag{24}$$

which is the final result.

Wait's expression for E_z^{VE} is[1]

$$E_z^{VE} \sim \frac{i60pk}{\text{[illegible]}} W \; . \tag{25}$$

Therefore,

$$W \sim \frac{e^{-\alpha\rho}}{(k\rho)^2}\left[V(t) + \frac{i\pi}{2} G(u)x^2 H_0^{(2)}(x)\right] , \tag{26}$$

which, for $x \leq 0.25$, reduces to

$$W \sim \frac{1}{(k\rho)^2}\left\{V(t) - G(u)x^2\left[\ln\left(\frac{1.123}{x}\right) - \frac{i\pi}{2}\right]\right\} . \tag{27}$$

The magnitude of W (from equation (26)) is compared with Wait's infinite sum-of-images result[1] in figure 3 as a function of distance and frequency. For this particular comparison, $h = 90$ km and $\sigma_i = \infty$ (i.e., $c/v = 1.0$ and $\alpha = 0.0$). Note that the agreement is excellent.

From equation (27), we see that the minimum value of W will occur when $V(t) \sim G(u)x^2 \ln(1.123/x)$. That is,

$$W_{MIN} \sim \frac{i\pi}{2} G(u)(c/v)^2 . \tag{28}$$

When $u > 2.5$,

$$W_{MIN} \sim iu(c/v)^2 = i\left(\frac{\pi\rho}{2h}\right)(c/v)^2 . \tag{29}$$

FIELD-STRENGTH FORMULAS

In this section, we will present new formulas for HED, HMD, and VED ELF radio-wave propagation in the earth-ionosphere waveguide. All of these formulas have been obtained by following the procedure outlined in the previous section. They are valid for $\rho > \lambda_e$, with no restrictions on the ratio of ρ to h.

It should be noted that for 2 Mm $\leq \rho \leq$ 19 Mm, all of the field-strength-component formulas presented in this report should be multiplied by the spherical earth spreading factor S, which is equal to

$$S = \left[\frac{\rho/a}{\sin(\rho/a)}\right]^{\nu} , \tag{30}$$

where $\nu = 1/2$ for all E_ρ, E_z, and H_ϕ components; $\nu = 3/2$ for all E_ϕ and H_ρ components; and a is the radius of the earth (~ 6.37 Mm).

FOR THE VED

Expressions for the VED are

$$E_\rho^{VE} \sim - \frac{\eta_e p G(u) e^{-\alpha\rho}}{2\pi\rho^2}\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{31}$$

$$E_z^{VE} \sim \frac{i60pe^{-\alpha\rho}}{k\rho^3}\left[V(t) + \frac{i\pi}{2} G(u)x^2H_0^{(2)}(x)\right] , \tag{24}$$

and

$$H_\phi^{VE} \sim \frac{pG(u)e^{-\alpha\rho}}{2\pi\rho^2}\left[\left(- \frac{i\pi}{2}\right)H_1^{(2)}(x)\right] . \tag{14}$$

The various VED components are related by

$$\frac{E_\rho^{VE}}{H_\phi^{VE}} \sim -\eta_e = \left(\frac{i\omega\mu_0}{\sigma_e + i\omega\varepsilon_e}\right)^{1/2} , \tag{32}$$

$$\frac{E_z^{VE}}{H_\phi^{VE}} \sim \frac{i\eta_0(c/v)}{xG(u)}\left[\frac{V(t) + \frac{i\pi}{2} G(u)x^2H_0^{(2)}(x)}{\left(- \frac{i\pi x}{2}\right)H_1^{(2)}(x)}\right] , \tag{33}$$

and

$$\frac{E_z^{VE}}{E_\rho^{VE}} \sim \frac{i\eta_0(c/v)}{\eta_e xG(u)}\left[\frac{V(t) + \frac{i\pi}{2} G(u)x^2H_0^{(2)}(x)}{\left(- \frac{i\pi x}{2}\right)H_1^{(2)}(x)}\right] , \tag{34}$$

where η_0 (= 120π) is the free-space impedance and η_e is the earth impedance.

FOR THE HED

Expressions for the HED are

$$E_\rho^{HE} \sim \left[\frac{pG(t) \cos \phi e^{-\alpha\rho}}{2\pi(\sigma_e + i\omega\varepsilon_e)\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)f(x)\right] , \tag{35}$$

$$E_\phi^{HE} \sim \left[- \frac{pH(t) \sin \phi e^{-\alpha\rho}}{2\pi(\sigma_e + i\omega\varepsilon_e)\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{36}$$

$$E_z^{HE} \sim \left[\frac{i\omega\mu_0 pG(u) \cos \phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{37}$$

$$H_\rho^{HE} \sim \left[\frac{pH(t) \sin \phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{38}$$

and

$$H_\phi^{HE} \sim \left[- \frac{pG(t) \cos \phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)f(x)\right] , \tag{39}$$

where

$$f(x) = 1 - x\left[\frac{H_0^{(2)}(x)}{H_1^{(2)}(x)}\right] . \tag{40}$$

The magnitude of f(x) is plotted in figure 4 versus x. For small values of x, $f(x) \sim 1$, while for large values of x, $f(x) \sim x$.

The various HED components are related by

$$\frac{E_\phi^{HE}}{H_\rho^{HE}} \sim - \frac{E_\rho^{HE}}{H_\phi^{HE}} \sim \eta_e , \tag{41}$$

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim - \frac{i\eta_0 x G(u)}{(c/v) f(x) G(t)} , \tag{42}$$

$$\frac{E_z^{HE}}{E_\rho^{HE}} \sim \frac{i\eta_0 x G(u)}{\eta_e (c/v) f(x) G(t)} , \tag{43}$$

and

$$\frac{H_\phi^{HE}}{H_\rho^{HE}} \sim \frac{E_\rho^{HE}}{E_\phi^{HE}} \sim - \frac{G(t)}{H(t)} f(x) \cot \phi \left[\frac{\sin(\rho/a)}{(\rho/a)}\right] . \tag{44}$$

FOR THE HMD

Expressions for the HMD are

$$E_\rho^{HM} \sim \left[\frac{m\eta_e G(t) \cos \phi e^{-\alpha\rho}}{2\pi\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x) f(x)\right] , \tag{45}$$

$$E_\phi^{HM} \sim \left[- \frac{m\eta_e G(t) \sin \phi e^{-\alpha\rho}}{2\pi\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x)\right] , \tag{46}$$

$$E_z^{HM} \sim \left[\frac{i\omega\mu_0 m G(u) \cos \phi e^{-\alpha\rho}}{2\pi\rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x)\right] , \tag{47}$$

$$H_\rho^{HM} \sim \left[\frac{m H(t) \sin \phi e^{-\alpha\rho}}{2\pi\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x)\right] , \tag{48}$$

and

$$H_z^{HM} \sim \left[- \frac{m G(t) \cos \phi e^{-\alpha\rho}}{2\pi\rho^3}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x) f(x)\right] . \tag{49}$$

The various HMD field components are related by

$$\frac{E_\phi^{HM}}{H_\rho^{HM}} \sim - \frac{E_\rho^{HM}}{H_\phi^{HM}} \sim \eta_e \ , \tag{50}$$

$$\frac{E_z^{HM}}{H_\phi^{HM}} \sim - \frac{i\eta_0 x G(u)}{(c/v) f(x) G(t)} \ , \tag{51}$$

$$\frac{E_z^{HM}}{E_\rho^{HM}} \sim \frac{i\eta_0 x G(u)}{\eta_e (c/v) f(x) G(t)} \ , \tag{52}$$

and

$$\frac{H_\phi^{HM}}{H_\rho^{HM}} \sim \frac{E_\rho^{HM}}{E_\phi^{HM}} \sim - \frac{G(t)}{H(t)} f(x) \cot \phi \left[\frac{\sin(\rho/a)}{(\rho/a)}\right] . \tag{53}$$

FIELD-STRENGTH FORMULAS FOR $x \leq 0.25$

When $x = k\rho(c/v) \leq 0.25$, $f(x) \sim 1.0$, and the Hankel functions can be approximated by

$$\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x) \sim 1.0 \tag{54}$$

and

$$H_0^{(2)}(x) \sim \frac{i2}{\pi}\left[\ln\left(\frac{1.123}{x}\right) - \frac{i\pi}{2}\right] . \tag{55}$$

Thus, the VED expressions listed in the previous section reduce to

$$E_\rho^{VE} \sim - \frac{\eta_e p G(u) e^{-\alpha\rho}}{2\pi\rho^2} \ , \tag{56}$$

$$E_z^{VE} \sim \frac{i60pe^{-\alpha\rho}}{k\rho^3}\left\{V(t) - G(u)x^2\left[\ln\left(\frac{1.123}{x}\right) - \frac{i\pi}{2}\right]\right\} , \tag{57}$$

$$H_\phi^{VE} \sim \frac{pG(u)e^{-\alpha\rho}}{2\pi\rho^2} \ , \tag{58}$$

$$\frac{E_z^{VE}}{H_\phi^{VE}} \sim \frac{i\eta_0}{(k\rho)G(u)}\left\{V(t) - G(u)x^2\left[\ln\left(\frac{1.123}{x}\right) - \frac{i\pi}{2}\right]\right\} , \tag{59}$$

and

$$\frac{E_z^{VE}}{E_\rho^{VE}} \sim \frac{-i\eta_0}{\eta_e(k\rho)G(u)}\left\{V(t) - G(u)x^2\left[\ell n\left(\frac{1.123}{x}\right) - \frac{i\pi}{2}\right]\right\} . \tag{60}$$

When $x \le 0.25$, the HED expressions listed in the previous section reduce to

$$E_\rho^{HE} \sim \frac{pG(t)\cos\phi e^{-\alpha\rho}}{2\pi(\sigma_e + i\omega\varepsilon_e)\rho^3} , \tag{61}$$

$$E_\phi^{HE} \sim -\frac{pH(t)\sin\phi e^{-\alpha\rho}}{2\pi(\sigma + i\omega\varepsilon_e)\rho^3} , \tag{62}$$

$$E_z^{HE} \sim \frac{i\omega\mu_0 pG(u)\cos\phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^2} , \tag{63}$$

$$H_\rho^{HE} \sim \frac{pH(t)\sin\phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^3} , \tag{64}$$

$$H_\phi^{HE} \sim -\frac{pG(t)\cos\phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^3} , \tag{65}$$

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim -\frac{i\eta_0 k\rho G(u)}{G(t)} , \tag{66}$$

$$\frac{E_z^{HE}}{E_\rho^{HE}} \sim \frac{i\eta_0 k\rho G(u)}{\eta_e G(t)} , \tag{67}$$

and

$$\frac{H_\phi^{HE}}{H_\rho^{HE}} \sim \frac{E_\rho^{HE}}{E_\phi^{HE}} \sim -\frac{G(t)}{H(t)}\cot\phi . \tag{68}$$

When $x \le 0.25$, the HMD expressions listed in the previous section reduce to

$$E_\rho^{HM} \sim \frac{m\eta_e G(t)\cos\phi e^{-\alpha\rho}}{2\pi\rho^3} , \tag{69}$$

$$E_\phi^{HM} \sim \frac{m\eta_e H(t)\sin\phi e^{-\alpha\rho}}{2\pi\rho^3} , \tag{70}$$

$$E_z^{HM} \sim \frac{i\omega\mu_0 mG(u)\cos\phi e^{-\alpha\rho}}{2\pi\rho^3} , \tag{71}$$

$$H_{\rho}^{HM} \sim \frac{mH(t)\ \sin\phi e^{-\alpha\rho}}{2\pi\rho^3} , \tag{72}$$

$$H_{\phi}^{HM} \sim -\frac{mG(t)\ \cos\phi e^{-\alpha\rho}}{2\pi\rho^3} , \tag{73}$$

$$\frac{E_z^{HM}}{H_{\phi}^{HM}} \sim -\frac{i\eta_0 k\rho G(u)}{G(t)} , \tag{74}$$

$$\frac{E_z^{HM}}{E_{\rho}^{HM}} \sim \frac{i\eta_0 k\rho G(u)}{\eta_e G(t)} , \tag{75}$$

and

$$\frac{H_{\phi}^{HM}}{H_{\rho}^{HM}} \sim \frac{E_{\rho}^{HM}}{E_{\phi}^{HM}} \sim -\frac{G(t)}{H(t)} \cot\phi . \tag{76}$$

When $\rho < h/3$, $G(u) \sim G(t) \sim V(t) \sim 1.0$, $H(t) \sim 2$, and $\alpha\rho \sim 0$. For this case, the formulas presented in this section (equations (56) through (76)), reduce to the familiar quasi-nearfield range results.[5-8] They will not be repeated here since they are already given by equations (56) through (76) with $G(u) \sim G(t) \sim V(t) \sim 1.0$, $H(t) \sim 2.0$, and $\alpha\rho = 0$.

FIELD-STRENGTH FORMULAS FOR $\rho > 3h$

When $\rho > 3h$,

$$G(u) \sim \frac{2u}{\pi} = \frac{\rho}{h} , \tag{77}$$

$$G(t) \sim H(t) \sim \frac{2t}{\pi} = \frac{\rho}{h(c/v)^2} , \tag{78}$$

and

$$V(t) \sim 0 . \tag{79}$$

For this case, the general field-strength formulas presented in equations (31) through (53) reduce to those of Wait[1] and Galejs.[2] For the sake of completeness, they will be repeated here.

FOR THE VED

Expressions for the VED are

$$E_\rho^{VE} = -\frac{\eta_e p e^{-\alpha\rho}}{2\pi h\rho}\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{80}$$

$$E_z^{VE} = -\frac{\eta_0 p(c/v)xH_0^{(2)}(x)e^{-\alpha\rho}}{4\pi h\rho} , \tag{81}$$

$$H_\phi^{VE} = \frac{pe^{-\alpha\rho}}{2\pi h\rho}\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{82}$$

$$\frac{E_z^{VE}}{H_\phi^{VE}} = -\eta_0(c/v)\frac{H_0^{(2)}(x)}{H_1^{(2)}(x)} , \tag{83}$$

and

$$\frac{E_z^{VE}}{E_\rho^{VE}} = \frac{\eta_0(c/v)}{\eta_e}\left[\frac{H_0^{(2)}(x)}{H_1^{(2)}(x)}\right] . \tag{84}$$

FOR THE HED

Expressions for the HED are

$$E_\rho^{HE} = \left[\frac{p\cos\phi e^{\alpha\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h(c/v)^2\rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)f(x)\right] , \tag{85}$$

$$E_\phi^{HE} = \left[-\frac{p\sin\phi e^{-\alpha\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h(c/v)^2\rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{86}$$

$$E_z^{HE} = \left[\frac{i\omega\mu_0 p\cos\phi e^{-\alpha\rho}}{2\pi\gamma_e h\rho}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{87}$$

$$H_\rho^{HE} = \left[\frac{p\sin\phi e^{-\alpha\rho}}{2\pi\gamma_e h(c/v)^2\rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)\right] , \tag{88}$$

$$H_\phi^{HE} = \left[-\frac{p\cos\phi e^{-\alpha\rho}}{2\pi\gamma_e h(c/v)^2\rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)f(x)\right] , \tag{89}$$

$$\frac{E_z^{HE}}{H_\phi^{HE}} = -\frac{i\eta_0(c/v)x}{f(x)} , \tag{90}$$

$$\frac{E_z^{HE}}{E_\rho^{HE}} \sim \frac{i\eta_0 (c/v) x}{\eta_e f(x)} , \tag{91}$$

and

$$\frac{H_\phi^{HE}}{H_\rho^{HE}} \sim \frac{E_\rho^{HE}}{E_\phi^{HE}} \sim -f(x) \cot \phi \left[\frac{\sin(\rho/a)}{(\rho/a)}\right] . \tag{92}$$

FOR THE HMD

Expressions for the HMD are

$$E_\rho^{HM} \sim \left[\frac{m\eta_e \cos \phi e^{-\alpha\rho}}{2\pi h (c/v)^2 \rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x) f(x)\right] , \tag{93}$$

$$E_\phi^{HM} \sim \left[- \frac{m\eta_e \sin \phi e^{-\alpha\rho}}{2\pi h (c/v)^2 \rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x)\right] , \tag{94}$$

$$E_z^{HM} \sim \left[\frac{i\omega\mu_0 m \cos \phi e^{-\alpha\rho}}{2\pi h \rho}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x)\right] , \tag{95}$$

$$H_\rho^{HM} \sim \left[\frac{m \sin \phi e^{-\alpha\rho}}{2\pi h (c/v)^2 \rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x)\right] , \tag{96}$$

$$H_\phi^{HM} \sim \left[- \frac{m \cos \phi e^{-\alpha\rho}}{2\pi h (c/v)^2 \rho^2}\right]\left[\left(\frac{-i\pi x}{2}\right) H_1^{(2)}(x) f(x)\right] , \tag{97}$$

$$\frac{E_z^{HM}}{H_\phi^{HM}} \sim - \frac{i\eta_0 (c/v) x}{f(x)} , \tag{98}$$

$$\frac{E_z^{HM}}{E_\rho^{HM}} \sim \frac{i\eta_0 (c/v) x}{\eta_e f(x)} , \tag{99}$$

and

$$\frac{H_\phi^{HM}}{H_\rho^{HM}} \sim \frac{E_\rho^{HM}}{E_\phi^{HM}} \sim -f(x) \cot \phi \left[\frac{\sin(\rho/a)}{(\rho/a)}\right] . \tag{100}$$

FIELD-STRENGTH FORMULAS FOR $\rho > 3h$ AND $x > 1.6$

For $x > 1.6$, the Hankel functions can be approximated by

$$H_0^{(2)}(x) \sim \sqrt{\frac{2}{\pi x}}\, e^{-i(x-\pi/4)} \ , \tag{101}$$

$$H_1^{(2)}(x) \sim i\sqrt{\frac{2}{\pi x}}\, e^{-i(x-\pi/4)} \ , \tag{102}$$

$$\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x) \sim \sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ , \tag{103}$$

and

$$\left(\frac{-i\pi x}{2}\right)H_1^{(2)}(x)f(x) \sim ix\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ . \tag{104}$$

Thus, the VED expressions listed in the previous section reduce to

$$E_\rho^{VE} \sim -\frac{\eta_e p e^{-\alpha\rho}}{2\pi h\rho}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ , \tag{105}$$

$$E_z^{VE} \sim -\frac{\eta_0 p(c/v)e^{-\alpha\rho}}{2\pi h\rho}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ , \tag{106}$$

$$H_\phi^{VE} \sim \frac{p e^{-\alpha\rho}}{2\pi h\rho}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ , \tag{107}$$

$$\frac{E_z^{VE}}{H_\phi^{VE}} \sim -\eta_0(c/v) \ , \tag{108}$$

and

$$\frac{E_z^{VE}}{E_\rho^{VE}} \sim -(\eta_0/\eta_e)(c/v) \ . \tag{109}$$

When $x > 1.6$, the HED expressions listed in the previous section reduce to

$$E_\rho^{HE} \sim \frac{p\cos\phi\, e^{-\alpha\rho}(ix)}{2\pi(\sigma_e + i\omega\varepsilon_e)h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ , \tag{110}$$

$$E_\phi^{HE} \sim -\frac{p\sin\phi\, e^{-\alpha\rho}}{2\pi(\sigma_e + i\omega\varepsilon_e)h(c/v)^2\rho}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \ , \tag{111}$$

$$E_z^{HE} \sim \frac{i\omega\mu_0 p \cos\phi e^{-\alpha\rho}}{2\pi\gamma_e h\rho}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{112}$$

$$H_\rho^{HE} \sim \frac{p \sin\phi e^{-\alpha\rho}}{2\pi\gamma_e h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{113}$$

$$H_\phi^{HE} \sim -\frac{p \cos\phi e^{-\alpha\rho}(ix)}{2\pi\gamma_e h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{114}$$

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim -\eta_0(c/v) \;, \tag{115}$$

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim (\eta_0/\eta_e)(c/v) \;, \tag{116}$$

and

$$\frac{H_\phi^{HE}}{H_\rho^{HE}} \sim \frac{E_\rho^{HE}}{E_\phi^{HE}} \sim ix \cot\phi\left[\frac{\sin(\rho/a)}{(\rho/a)}\right] . \tag{117}$$

When $x > 1.6$, the HMD expressions listed in the previous section reduce to

$$E_\rho^{HM} \sim \frac{m\eta_e \cos\phi e^{-\alpha\rho}(ix)}{2\pi h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{118}$$

$$E_\phi^{HM} \sim \frac{-m\eta_e \sin\phi e^{-\alpha\rho}}{2\pi h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{119}$$

$$E_z^{HM} \sim \frac{i\omega\mu_0 m \cos\phi e^{-\alpha\rho}}{2\pi h\rho}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{120}$$

$$H_\rho^{HM} \sim \frac{m \sin\phi e^{-\alpha\rho}}{2\pi h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{121}$$

$$H_\phi^{HM} \sim -\frac{m \cos\phi e^{-\alpha\rho}(ix)}{2\pi h(c/v)^2\rho^2}\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \;, \tag{122}$$

$$\frac{E_z^{HM}}{H_\phi^{HM}} \sim -\eta_0(c/v) \;, \tag{123}$$

$$\frac{E_z^{HM}}{E_\phi^{HM}} \sim (\eta_0/\eta_e)(c/v) \;, \tag{124}$$

and

$$\frac{H_{\phi}^{HM}}{H_{\rho}^{HM}} \sim \frac{E_{\rho}^{HM}}{E_{\phi}^{HM}} \sim -ix \cot \phi \left[\frac{\sin(\rho/a)}{(\rho/a)}\right] . \tag{125}$$

DISCUSSION

We have used[9] the recently developed theory of Greifinger and Greifinger[10-12] and the Wait exponential ionospheric-conductivity profile to determine average ELF propagation constants for both daytime and nighttime propagation conditions. The resulting average values of ELF attenuation rate, phase-velocity ratio, and ionospheric reflection height (presented in table 1) are in excellent agreement with measured data.[9]

To shed further light on the nature of the ELF field strengths in the earth-ionosphere waveguide, the radial impedance of the wave (E_z/H_{ϕ}) now is

Table 1. Typical ELF Propagation Parameters

Frequency (Hz)	Time of Day	h (km)	c/v	α (dB/Mm)
30	Day	46.1	1.34	0.6
50	Day	47.8	1.30	1.0
75	Day	49.1	1.27	1.5
100	Day	50.1	1.25	2.0
150	Day	51.4	1.22	2.8
200	Day	52.4	1.20	3.7
300	Day	53.7	1.18	5.4
30	Night	72.0	1.12	0.6
50	Night	73.3	1.11	0.8
75	Night	74.5	1.10	1.0
100	Night	75.0	1.09	1.2
150	Night	76.0	1.09	1.6
200	Night	76.8	1.08	2.0
300	Night	77.8	1.07	2.7

considered. By definition, this quantity is the impedance of the wave looking in the radial, or ρ, direction.

For $x >> 1$,

$$\frac{E_z}{H_\phi} \sim -\eta_0 (c/v) \ , \tag{126}$$

while, for $x << 1$ and $\rho < h/3$,

$$\frac{E_z^{VE}}{H_\phi^{VE}} \sim - \frac{\eta_0}{ik\rho} \tag{127}$$

and

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim \frac{E_z^{HM}}{H_\phi^{HM}} \sim -ik\rho\eta_0 \ . \tag{128}$$

For the intermediate, and most interesting, range,

$$\frac{E_z^{VE}}{H_\phi^{VE}} \sim \frac{i\eta_0 (c/v)}{xG(u)} \left[\frac{V(t) + \frac{i\pi}{2} G(u) x^2 H_0^{(2)}(x)}{\frac{-i\pi x}{2} H_1^{(2)}(x)} \right] \tag{33}$$

and

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim \frac{E_z^{HM}}{H_\phi^{HM}} \sim - \frac{i\eta_0 x G(u)}{(c/v) f(x) G(t)} \ , \tag{42}$$

while, for $x \leq 0.25$, equations (33) and (42) reduce to

$$\frac{E_z^{VE}}{H_\phi^{VE}} \sim \frac{i\eta_0}{(k\rho) G(u)} \left\{ V(t) - G(u) x^2 \left[\ln\left(\frac{1.123}{x}\right) - \frac{i\pi}{2} \right] \right\} \tag{59}$$

and

$$\frac{E_z^{HE}}{H_\phi^{HE}} \sim \frac{E_z^{HM}}{H_\phi^{HM}} \sim - \frac{i\eta_0 k\rho G(u)}{G(t)} \ . \tag{60}$$

Referring to equation (59), we see that the minimum value of E_z^{VE}/H_ϕ^{VE} will occur when $V(t) = G(u)x^2 \ln(1.123/x)$. That is,

$$\left|\frac{E_z^{VE}}{H_\phi^{VE}}\right|_{MIN} \sim (120\pi)(\pi/2)(k\rho)(c/v)^2$$

$$= 60\pi^2(k\rho)(c/v)^2 \ . \qquad (129)$$

Alternatively, the approximate distance from the VED source where the minimum value of radial wave impedance occurs, ρ_{mv}, can be expressed as (from equation (129))

$$\rho_{mv} \sim \frac{80.63\left|E_z^{VE}/H_\phi^{VE}\right|_{min}}{f(c/v)^2} \ \text{km} \ . \qquad (130)$$

Presented in figures 5 and 6 are plots of the VED radial wave impedance versus distance for frequencies of 30 to 300 Hz. Equation (33) and the values of h and c/v listed in table 1 were used in the calculations. Note that, for frequencies of 30 to 100 Hz, there is a unique distance where the minimum value of radial wave impedance occurs. Presented in table 2 are values of ρ_{mv} calculated from equation (130). Comparing these values with the curves of figures 5 and 6 reveals that the table-2 ρ_{mv} calculations are accurate within 10 km.

Presented in figures 7 and 8 are plots of the HED and HMD radial wave impedance versus distance for frequencies of 30 to 300 Hz. Equation (42) and the values of h and c/v listed in table 1 were used in the calculations.

Table 2. Approximate Distance Where the Minimum Value of the VED Radial Wave Impedance Occurs

Frequency (Hz)	Time of Day	Minimum E_z/H_ϕ (ohms)	Approximate ρ_{mv} (km)
30	Day	120	180
50	Day	170	162
75	Day	220	147
100	Day	270	139
30	Night	95	204
50	Night	140	183
75	Night	190	169
100	Night	230	156

Referring to figures 5 through 8, we see that there is a substantial variation in both the VED and HED radial wave impedance. For example, at 30 Hz, the VED wave impedance is equal to 30,000 ohms to 20 km, 120 ohms at 180 km, and 505 ohms ($120\pi c/v$) at 5,000 km (figure 5). On the other hand, the 30-Hz HED (or HMD) wave impedance varies from 5 ohms at 20 km to 505 ohms at 5,000 km (figure 7).

As Wait[1] has pointed out, the observed variation of the magnitude and/or phase of the radial wave impedance as a function of frequency should provide a basis for distance measuring (provided the atmospheric source could be represented by an equivalent VED or HED). Such a scheme, while admittedly crude, requires only one receiving station equipped with a vertical whip and loop antenna.

CONCLUSIONS

In this report, we have presented new formulas for HED, HMD, and VED ELF radio-wave propagation in the earth-ionosphere waveguide. These new formulas extend the results of Wait[1] and Galejs,[2] which are valid for measurement distances greater than approximately three ionospheric reflecting heights, down to the quasi-nearfield range, which is defined as the range where the measurement distance is greater than an earth wavelength but much less than a free-space wavelength. For the sake of completeness, the abovementioned previously derived formulas also have been included.

Plots of the VED, HED, and HMD radial wave impedance versus distance have been presented for both daytime and nighttime propagation conditions. These plots show a substantial variation in the radial wave impedances for distances less than 1,000 km. Also, we have shown that there is a unique distance where the minimum value of the VED radial wave impedance occurs.

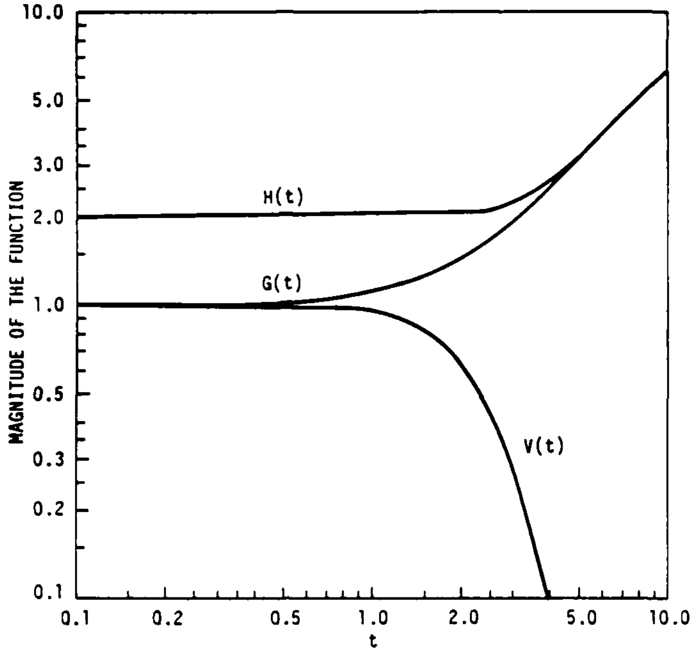

Figure 1. Magnitude of the Functions G(t), H(t), and V(t) Versus t

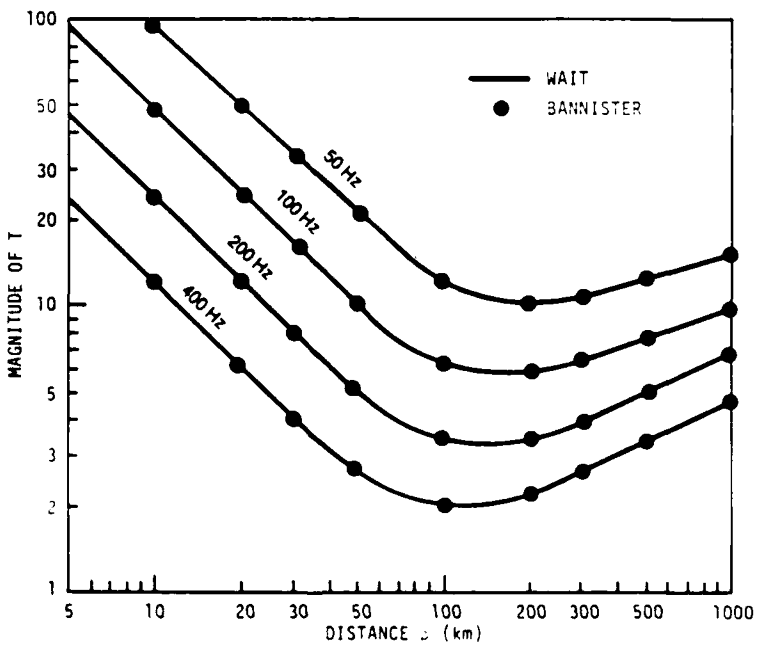

Figure 2. Magnitude of the Function T Versus Distance

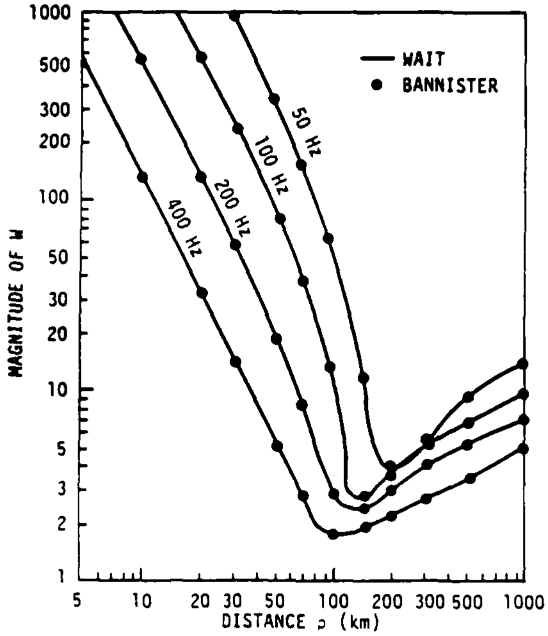

Figure 3. Magnitude of the Function W Versus Distance

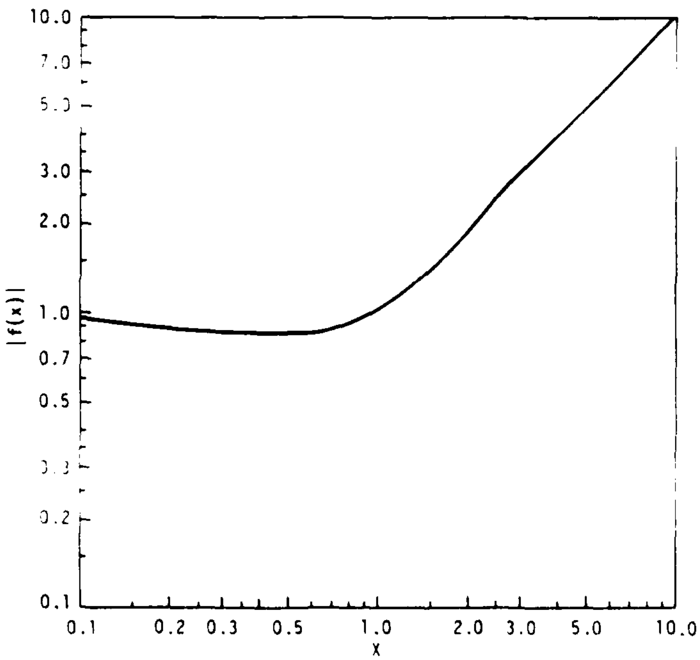

Figure 4. Magnitude of the Function f(x) Versus x

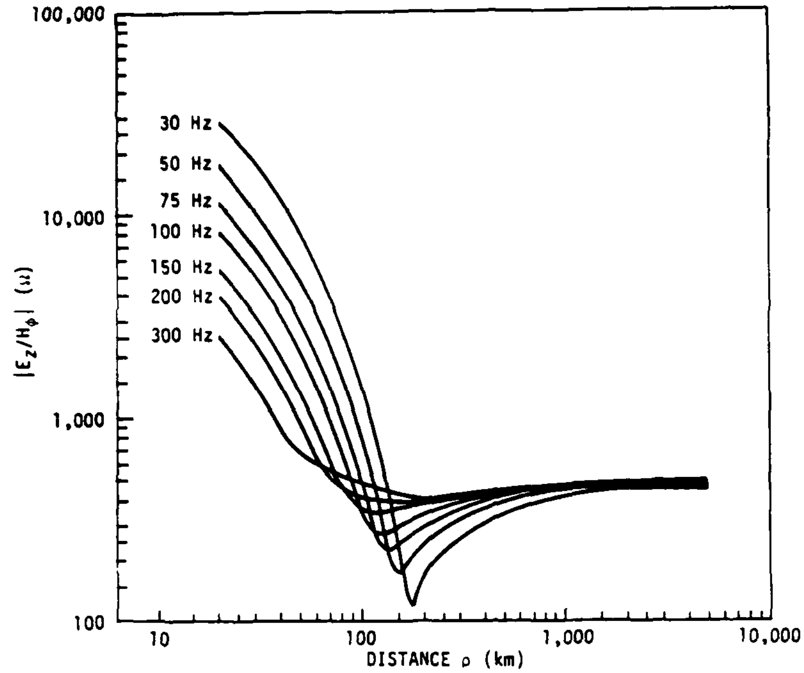

Figure 5. VED Radial Wave Impedance Versus Distance for Daytime Propagation Conditions

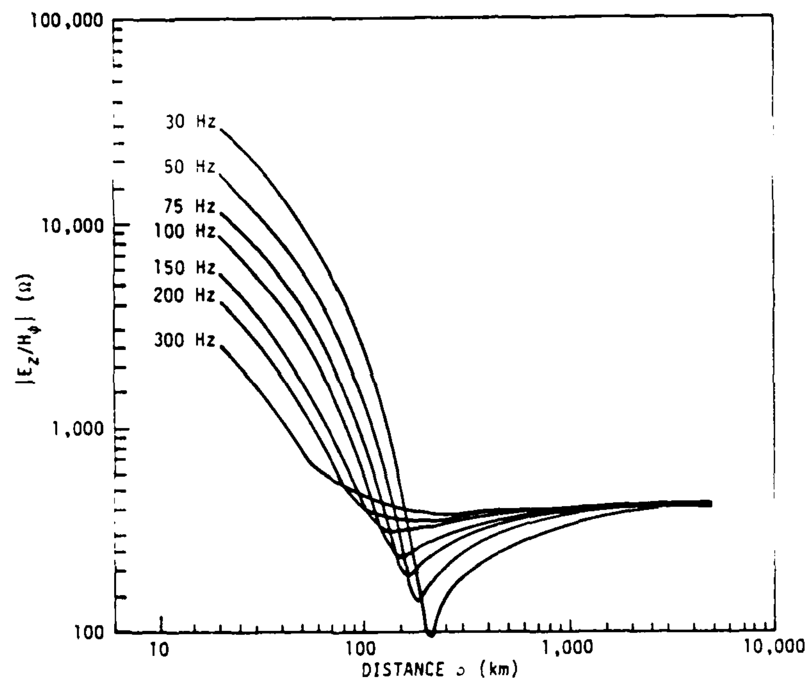

Figure 6. VED Radial Wave Impedance Versus Distance for Nighttime Propagation Conditions

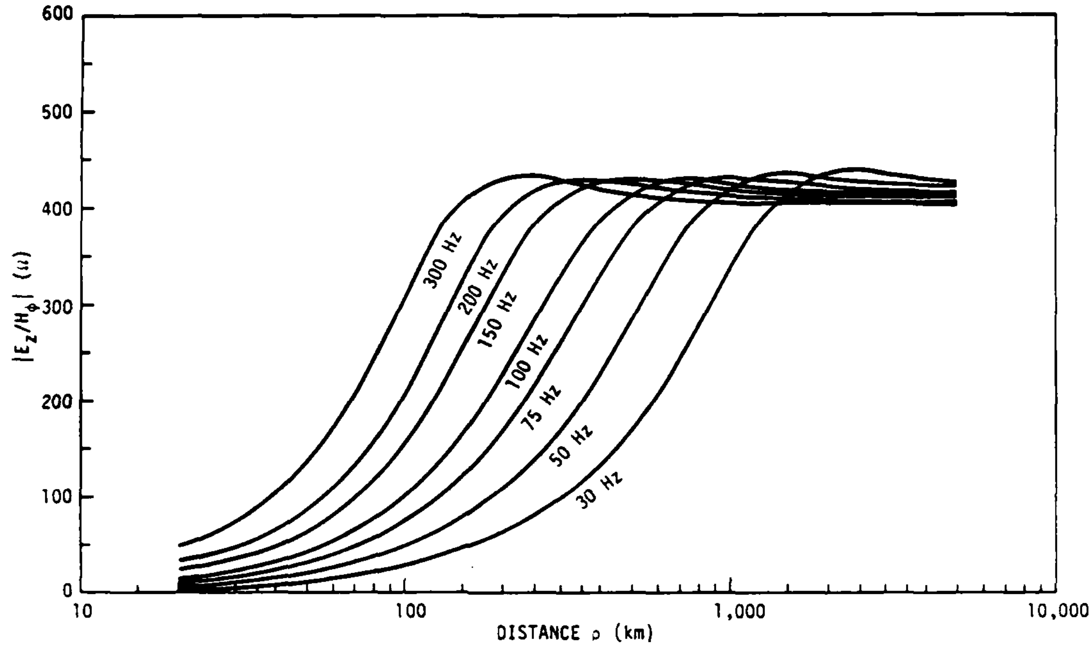

Figure 7. HED and HMD Radial Wave Impedance Versus Distance for Daytime Propagation Conditions

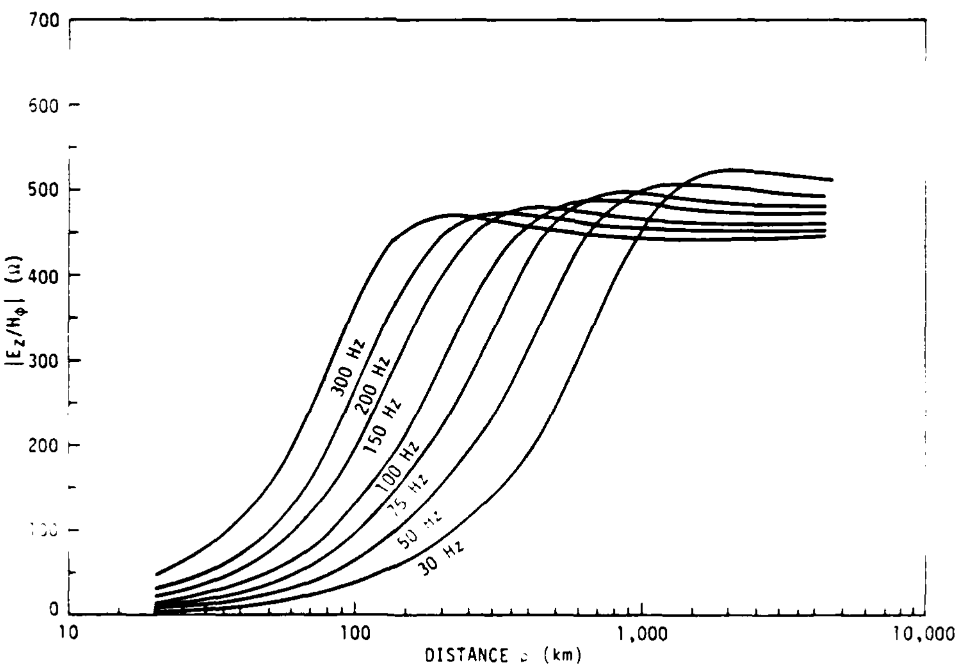

Figure 8. HED and HMD Radial Wave Impedance Versus Distance for Nighttime Propagation Conditions

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12. C. Greifinger and P. Greifinger, Extended Theory for Approximate ELF Propagation Constants in the Earth-Ionosphere Waveguide, DNA Report No. 5561T, R and D Associates, Marina Del Rey, CA, 1979.

Appendix

E/H CALCULATION PROGRAMS

Five programs were written to solve for E/H fields at various distances from a transmission source. The following cases were considered:

1. E_z/H_ϕ of an HED source, nearfield approximation;
2. E_z/H_ϕ of a VED source, nearfield approximation;
3. E_z/H_ρ of an HED source, nearfield approximation;
4. E_z/H_ϕ of an HED source, farfield approximation; and
5. E_z/H_ϕ of a VED source, farfield approximation.

The programs are written in VAX-11 FORTRAN. They reside as executable modules on the Naval Underwater Systems Center (NUSC) VAX system. They can be invoked by keying RUN 'filename' where the five files shown below correspond to the five cases listed above:

1. v703::DU01:[ETC.EHNEARFLD]EHHED;
2. v703::DU01:[ETC.EHNEARFLD]EHVED;
3. v703::DU01:[ETC.EHNEARFLD]EZHRHO;
4. v703::DU01:[ETC.EHFARFLD]EHHED; and
5. v703::DU01:[ETC.EHFARFLD]EHVED.

Each of the programs contains an interactive section in which the user enters parameters of interest. These parameters involve the range of distance from the source for which E/H is to be calculated, the frequency of interest, the time of day, and, sometimes, the angle from the zenith.

Listings are provided for each of the programs created. Program structure and flow are clearly indicated in the listings. Most of the program variables, such as T, GT (= G(t)), X, RHO, RFLHT (= ionospheric reflection height), CVEE (= c/v), TOP (= night or day values), etc., correspond exactly to the variables in the equations. It is suggested that the reader have the equations at hand, particularly when tracing the flow of the actual calculations, as the calculations follow the equations in a logical and consistent manner. These programs are pretty much 'number crunchers;' their flow is not complex.

Calls are made for calculation of hyperbolic functions and Hankel functions. The hyperbolic function routines also are written in VAX-11 FORTRAN; the listings for these routines have been included. The Hankel-function

calculation consists of calling the appropriate IMSL Bessel functions and combining them in the calling program, as the Hankel function is a combination of Bessel functions. The IMSL routines are available through the 'IMSLIBS' library on the VAX.

```
C***************************************************************
C       CREATED:         27FEB85                               *
C       LAST UPDATE:     07MAR85                               *
C       BY:              A. KUZEL                              *
C       PURPOSE:         FORTRAN PROGRAM TO CALCULATE THE VALUE *
C                        OF E/H FOR AN ELF WAVEFORM OF A SET OF *
C                        ALLOWED FREQUENCIES F AT VARIOUS      *
C                        DISTANCES, <= 200 KM, FROM A HED SOURCE. *
C                        THIS IS THE NEAR FIELD APPROXIMATION. *
C***************************************************************

C          *DECLARE VARIABLES*

           COMPLEX      I,H0,H1,HR,RAZ
           REAL         K,J0,J1,PI,RHO,FREQ,INC,MAXDIS,T,U,V,X,GT,Y0(1)
           REAL         CVEE,RFLHT,MMBSJ0,MMBSJ1,RAZA,RAZPH,Y1(1)
           CHARACTER    TOD

C          *INITIALIZE CONSTANTS*

           K=3.00E+05
           PI=4*ATAN(1.0)
           I=CMPLX(0.0,1.0)

C**********************************************************************
C    THE FOLLOWING SECTION IS THE INTERACTIVE PORTION OF THE PROGRAM.  *
C    THE USER CHOOSES STARTING DISTANCE, INCREMENT, AND ENDING DISTANCE *
C    TO CALCULATE, NIGHT OR DAY VALUES, AND THE FREQUENCY OF INTEREST. *
C**********************************************************************

           WRITE(5,200)
           READ(5,204)RHO
           WRITE(5,201)
           READ(5,204)INC
           WRITE(5,202)
           READ(5,204)MAXDIS
           WRITE(5,203)
           READ(5,204)FREQ
           WRITE(5,205)
           READ(5,206)TOD

C         *SELECT PROPER IONOSPHERIC REFLECTION HEIGHT AND
           C/V CONSTANTS BASED ON USER'S INPUT DATA*


           IF(FREQ.EQ.30) THEN
             IF(TOD.EQ.'D') THEN
               RFLHT=46.1
               CVEE=1.34
             END IF
             IF(TOD.EQ.'N') THEN
               RFLHT=72.0
               CVEE=1.12
             END IF
           END IF
           IF(FREQ.EQ.50) THEN
             IF(TOD.EQ.'D') THEN
               RFLHT=47.8
               CVEE=1.30
             END IF
             IF(TOD.EQ.'N') THEN
```

```
      RFLHT=73.3
      CVEE=1.11
    END IF
  END IF
  IF(FREQ.EQ.75) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=49.1
      CVEE=1.27
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=74.3
      CVEE=1.10
    END IF
  END IF
  IF(FREQ.EQ.100) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=50.1
      CVEE=1.25
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=75.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.150) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=51.4
      CVEE=1.22
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.200) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=52.4
      CVEE=1.20
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.8
      CVEE=1.08
    END IF
  END IF
  IF(FREQ.EQ.300) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=53.7
      CVEE=1.18
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=77.8
      CVEE=1.07
    END IF
  END IF

*WRITE HEADERS FOR OUTPUT TABLE*

  WRITE(10,220)
  WRITE(10,208)
  WRITE(10,207)FREQ
  IF(TOD.EQ.'D') WRITE(10,211)
```

```
          IF(TOD.EQ.'N') WRITE(10,212)
          WRITE(10,208)
          WRITE(10,209)
          WRITE(10,208)
C         *PERFORM THE ACTUAL CALCULATION*
400       X=2*PI*FREQ*RHO*CVEE/K
          T=RHO*PI/(2*RFLHT*CVEE**2)
          U=T
          V=T
          CALL COTH(U)
          CALL CSCH(V)
          GT=2*T/PI*U
          GT=GT+(1-2/PI)*T**2*V**2
          J0=MMBSJ0(X,IER)
          J1=MMBSJ1(X,IER)
          CALL MMBSYN(X,0.,1,Y0,IER)
          CALL MMBSYN(X,0.999,1,Y1,IER)
          H0=CMPLX(J0,-Y0(1))
          H1=CMPLX(J1,-Y1(1))
          HR=H0/H1
          RAZ=1-X*HR
          RAZ=1/RAZ
          RAZ=RAZ*120*PI*I*X
          RAZ=-RAZ
          U=RFLHT/RHO
          CALL TANH(U)
          RAZ=RAZ/(CVEE*GT*U)
          RAZA=CABS(RAZ)
          RAZPH=ATAN2(AIMAG(RAZ),REAL(RAZ))
          RAZPH=RAZPH*180.00/PI
          WRITE(10,210)RHO,RAZA,RAZPH
          RHO=RHO+INC
          IF(RHO.LE.MAXDIS) GO TO 400
C         *FORMAT STATEMENTS*
200       FORMAT(4X,'ENTER STARTING DISTANCE FROM SOURCE:')
201       FORMAT(4X,'ENTER DISTANCE INCREMENT:')
202       FORMAT(4X,'ENTER MAXIMUM DISTANCE TO COMPUTE:')
203       FORMAT(4X,'ENTER FREQUENCY:')
204       FORMAT(F12.4)
205       FORMAT(4X,'NIGHT (N) OR DAY (D)?:')
206       FORMAT(A2)
207       FORMAT(9X,'HORIZONTAL ELECTRIC DIPOLE    FREQ = ',F7.2)
208       FORMAT(5X,'    ')
209       FORMAT(11X,'DISTANCE',8X,'MAGNITUDE',9X,'PHASE')
210       FORMAT(10X,F7.2,10X,F7.2,10X,F7.2)
211       FORMAT(9X,'TOD = DAYTIME')
212       FORMAT(9X,'TOD = NIGHT')
220       FORMAT(9X,'E/H NEAR FIELD APPROXIMATION')
          STOP
          END
```

```
C*************************************************************
C       CREATED:         28FEB85                              *
C       LAST UPDATE:     07MAR85                              *
C       BY:              A. KUZEL                             *
C       PURPOSE:         FORTRAN PROGRAM TO CALCULATE THE VALUE *
C                        OF E/H FOR AN ELF WAVEFORM OF A SET OF *
C                        ALLOWED FREQUENCIES F AT VARIOUS      *
C                        DISTANCES, <= 200 KM, FROM THE VED SOURCE. *
C                        THIS IS THE NEAR FIELD APPROXIMATION. *
C*************************************************************

C          *DECLARE VARIABLES*

           COMPLEX      I,H0,H1,HR,RAZ
           REAL         K,J0,J1,PI,RHO,FREQ,INC,MAXDIS,T,U,V,X,GT,Y0(1)
           REAL         CVEE,RFLHT,MMBSJ0,MMBSJ1,RAZA,RAZPH,Y1(1)
           CHARACTER    TOD

C          *INITIALIZE CONSTANTS*

           K=3.00E+05
           PI=4*ATAN(1.0)
           I=CMPLX(0.0,1.0)

C*******************************************************************
C        THE FOLLOWING SECTION IS THE INTERACTIVE PORTION OF THE PROGRAM *
C    THE USER CHOOSES STARTING DISTANCE, INCREMENT, AND ENDING DISTANCE *
C    TO CALCULATE, NIGHT OR DAY VALUES, AND FREQUENCY OF INTEREST.     *
C*******************************************************************

           WRITE(5,200)
           READ(5,204)RHO
           WRITE(5,201)
           READ(5,204)INC
           WRITE(5,202)
           READ(5,204)MAXDIS
           WRITE(5,203)
           READ(5,204)FREQ
           WRITE(5,205)
           READ(5,206)TOD

C         *CHOOSE PROPER VALUES OF IONOSPHERIC REFLECTION HEIGHT AND
C          C/V CONSTANTS BASED ON USER'S INPUT DATA*


           IF(FREQ.EQ.30) THEN
             IF(TOD.EQ.'D') THEN
               RFLHT=46.1
               CVEE=1.34
             END IF
             IF(TOD.EQ.'N') THEN
               RFLHT=72.0
               CVEE=1.12
             END IF
           END IF
           IF(FREQ.EQ.50) THEN
             IF(TOD.EQ.'D') THEN
               RFLHT=47.8
               CVEE=1.30
             END IF
             IF(TOD.EQ.'N') THEN
```

```
      RFLHT=73.3
      CVEE=1.11
    END IF
  END IF
  IF(FREQ.EQ.75) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=49.1
      CVEE=1.27
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=74.3
      CVEE=1.10
    END IF
  END IF
  IF(FREQ.EQ.100) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=50.1
      CVEE=1.25
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=75.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.150) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=51.4
      CVEE=1.22
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.200) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=52.4
      CVEE=1.20
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.8
      CVEE=1.08
    END IF
  END IF
  IF(FREQ.EQ.300) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=53.7
      CVEE=1.18
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=77.8
      CVEE=1.07
    END IF
  END IF

  *WRITE HEADERS FOR OUTPUT TABLE*

  WRITE(10,220)
  WRITE(10,208)
  WRITE(10,207)FREQ
  IF(TOD.EQ.'D') WRITE(10,211)
```

```
      IF(TOD.EQ.'N') WRITE(10,212)
      WRITE(10,208)
      WRITE(10,209)
      WRITE(10,208)
C     *PERFORM THE ACTUAL CALCULATION*
400   X=2*PI*FREQ*RHO*CVEE/K
      T=RHO*PI/(2*RFLHT*CVEE**2)
      U=T
      V=T
      CALL COTH(U)
      CALL CSCH(V)
      GT=2*T/PI*U
      GT=GT+(1-2/PI)*T**2*V**2
      VT=T**3*V**2*U
      HT=VT+GT
      J0=MMBSJ0(X,IER)
      J1=MMBSJ1(X,IER)
      CALL MMBSYN(X,0.,1,Y0,IER)
      CALL MMBSYN(X,0.999,1,Y1,IER)
      H0=CMPLX(J0,-Y0(1))
      H1=CMPLX(J1,-Y1(1))
      RAZ=H0*X**2*CVEE**2*HT*(PI/2)*I
      RAZ=RAZ+VT
      RAZ=RAZ/(H1*X*PI*(-I)/2)
      U=RFLHT/RHO
      CALL TANH(U)
      RAZ=RAZ*U/X
      RAZ=RAZ*I*120*PI*CVEE
      RAZA=CABS(RAZ)
      RAZPH=ATAN2(AIMAG(RAZ),REAL(RAZ))
      RAZPH=RAZPH*180.00/PI
      WRITE(10,210)RHO,RAZA,RAZPH
      RHO=RHO+INC
      IF(RHO.LE.MAXDIS) GO TO 400
C     *FORMAT STATEMENTS*
200   FORMAT(4X,'ENTER STARTING DISTANCE FROM SOURCE:')
201   FORMAT(4X,'ENTER DISTANCE INCREMENT:')
202   FORMAT(4X,'ENTER MAXIMUM DISTANCE TO COMPUTE:')
203   FORMAT(4X,'ENTER FREQUENCY:')
204   FORMAT(F12.4)
205   FORMAT(4X,'NIGHT (N) OR DAY (D)?:')
206   FORMAT(A2)
207   FORMAT(10X,'VERTICAL ELECTRIC DIPOLE    FREQ = ',F7.2)
208   FORMAT(5X,'    ')
209   FORMAT(11X,'DISTANCE',8X,'MAGNITUDE',10X,'PHASE')
210   FORMAT(10X,F7.2,9X,F9.2,10X,F7.2)
211   FORMAT(12X,'TOD = DAYTIME')
212   FORMAT(12X,'TOD = NIGHT')
220   FORMAT(9X,'E/H  NEAR FIELD APPROXIMATION')
      STOP
      END
```

```
C*********************************************************************
C       CREATED:         01MAR85                                      *
C       LAST UPDATE:     01MAR85                                      *
C       BY:              A. KUZEL                                     *
C       PURPOSE:         FORTRAN PROGRAM TO CALCULATE THE VALUE       *
C                        OF E SUB Z OVER H SUB RHO FOR AN ELF         *
C                        WAVEFORM OF A SET OF ALLOWED FREQUENCIES F   *
C                        AT VARIOUS DISTANCES, <= 200 KM, FROM AN     *
C                        HED SOURCE, AT VARIUOS ANGLES FROM THE ZENITH. *
C                        THIS IS THE NEAR FIELD APPROXIMATION         *
C*********************************************************************

C          *DECLARE VARIABLES*

           COMPLEX      I,RAZ
           REAL         K,PI,RHO,FREQ,INC,MAXDIS,T,U,V,X,GT
           REAL         CVEE,RFLHT,RAZA,RAZPH,VT,HT,PHI
           CHARACTER    TOD

C          *INITIALIZE VARIABLES*

           K=3.00E+05
           PI=4*ATAN(1.0)
           I=CMPLX(0.0,1.0)

C*********************************************************************
C     THE FOLLOWING SECTION IS THE INTERACTIVE PORTION OF THE PROGRAM. *
C  THE USER CHOOSES STARTING DISTANCE, INCREMENT, AND ENDING DISTANCE  *
C  TO CALCULATE, NIGHT OR DAY VALUES, FREQUENCY OF INTEREST, AND ANGLE *
C  OF INTEREST.                                                        *
C*********************************************************************

           WRITE(5,200)
           READ(5,204)RHO
           WRITE(5,201)
           READ(5,204)INC
           WRITE(5,202)
           READ(5,204)MAXDIS
           WRITE(5,203)
           READ(5,204)FREQ
           WRITE(5,205)
           READ(5,206)TOD
           WRITE(5,213)
           READ(5,204)PHI

C         *SELECT PROPER IONOSPHERIC REFLECTION HEIGHT AND
C          C/V VALUES BASED ON USER'S INPUT DATA.*

           IF(FREQ.EQ.30) THEN
             IF(TOD.EQ.'D') THEN
               RFLHT=46.1
               CVEE=1.34
             END IF
             IF(TOD.EQ.'N') THEN
               RFLHT=72.0
               CVEE=1.12
             END IF
           END IF
           IF(FREQ.EQ.50) THEN
             IF(TOD.EQ.'D') THEN
               RFLHT=47.8
```

```
      CVEE=1.30
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=73.3
      CVEE=1.11
    END IF
  END IF
  IF(FREQ.EQ.75) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=49.1
      CVEE=1.27
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=74.3
      CVEE=1.10
    END IF
  END IF
  IF(FREQ.EQ.100) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=50.1
      CVEE=1.25
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=75.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.150) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=51.4
      CVEE=1.22
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.200) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=[illegible]
      CVEE=1.20
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.8
      CVEE=1.08
    END IF
  END IF
  IF(FREQ.EQ.300) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=53.7
      CVEE=1.18
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=77.8
      CVEE=1.07
    END IF
  END IF

*WRITE HEADERS FOR OUTPUT TABLE*

  WRITE(10,207)FREQ
```

```
      IF(TOD.EQ.'D') WRITE(10,211)PHI
      IF(TOD.EQ.'N') WRITE(10,212)PHI
      WRITE(10,208)
      WRITE(10,209)
      WRITE(10,208)
      PHI=PHI*PI/180.00

C     *PERFORM THE ACTUAL CALCULATION*

400   X=2*PI*FREQ*RHO*CVEE/K
      T=RHO*PI/(2*RFLHT*CVEE**2)
      U=T
      V=T
      CALL COTH(U)
      CALL CSCH(V)
      GT=2*T/PI*U
      GT=GT+(1-2/PI)*T**2*V**2
      VT=T**3*V**2*U
      HT=VT+GT
      U=(1/TAN(PHI))
      V=RFLHT/RHO
      CALL TANH(V)
      RAZ=I*120*PI*X*U
      RAZ=RAZ/(CVEE*HT*V)
      RAZA=CABS(RAZ)
      RAZPH=ATAN2(AIMAG(RAZ),REAL(RAZ))
      RAZPH=RAZPH*180.00/PI
      WRITE(10,210)RHO,RAZA,RAZPH
      RHO=RHO+INC
      IF(RHO.LE.MAXDIS) GO TO 400

C     *FORMAT STATEMENTS*

200   FORMAT(4X,'ENTER STARTING DISTANCE FROM SOURCE:')
201   FORMAT(4X,'ENTER DISTANCE INCREMENT:')
202   FORMAT(4X,'ENTER MAXIMUM DISTANCE TO COMPUTE:')
203   FORMAT(4X,'ENTER FREQUENCY:')
204   FORMAT(F12.4)
205   FORMAT(4X,'NIGHT (N) OR DAY (D)?:')
206   FORMAT(A2)
207   FORMAT(10X,'HED SOURCE  EZ/HRHO    FREQ = ',F7.2)
208   FORMAT(5X,'     ')
209   FORMAT(11X,'DISTANCE',8X,'MAGNITUDE',10X,'PHASE')
210   FORMAT(10X,F7.2,9X,F9.2,10X,F7.2)
211   FORMAT(12X,'TOD = DAYTIME    PHI = ',F5.2)
212   FORMAT(12X,'TOD = NIGHT      PHI = ',F5.2)
213   FORMAT(4X,'ENTER PHI IN DEGREES:')
      STOP
      END
```

```
C***************************************************************
C     DATE CREATED:  21FEB85                                  *
C     LAST UPDATE:   07MAR85                                  *
C     BY:             A. KUZEL                                *
C     PURPOSE:       THIS PROGRAM CALCULATES THE VALUE OF THE E/H *
C                    FIELD OF AN ELF WAVEFORM OF ONE OF A SET OF  *
C                    FREQUENCIES AT VARIOUS DISTANCES >= 200 KM   *
C                    FROM AN HED SOURCE.  THIS IS THE FAR FIELD   *
C                    APPROXIMATION.                               *
C***************************************************************

C           *DECLARE VARIABLES*

            COMPLEX      I,Y,H0,H1,HR
            REAL         J0,J1,Y0(1),Y1(1),MMBSJ0,MMBSJ1,MAXDIS
            REAL         RHO,INC,PI,CVEE,FREQ,FUDGE,X,VA,PH
            CHARACTER    TOD

C           *INITIALIZE CONSTANTS*

            PI=4*ATAN(1.0)
            I=CMPLX(0.0,1.0)

C*******************************************************************
C     THE FOLLOWING SECTION IS THE INTERACTIVE PORTION OF THE PROGRAM   *
C   THE USER CHOOSES STARTING DISTANCE, INCREMENT, AND ENDING DISTANCE  *
C   TO CALCULATE, NIGHT OR DAY VALUES, AND THE FREQUENCY OF INTEREST.   *
C*******************************************************************

            WRITE(5,540)
            READ(5,545)RHO
            WRITE(5,547)
            READ(5,560)INC
            FUDGE=3.0E+05
            WRITE(5,548)
            READ(5,545)MAXDIS
            WRITE(5,550)
            READ(5,560)FREQ
            WRITE(5,205)
            READ(5,206)TOD

C           *SELECT PROPER IONOSPHERIC REFLECTION HEIGHT AND
C            C/V CONSTANTS BASED ON USERS INPUT DATA*

            IF(FREQ.EQ.30) THEN
              IF(TOD.EQ.'D') THEN
                RFLHT=46.1
                CVEE=1.34
              END IF
              IF(TOD.EQ.'N') THEN
                RFLHT=72.0
                CVEE=1.12
              END IF
            END IF
            IF(FREQ.EQ.50) THEN
              IF(TOD.EQ.'D') THEN
                RFLHT=47.8
                CVEE=1.30
              END IF
              IF(TOD.EQ.'N') THEN
                RFLHT=73.3
```

```
      CVEE=1.11
    END IF
  END IF
  IF(FREQ.EQ.75) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=49.1
      CVEE=1.27
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=74.3
      CVEE=1.10
    END IF
  END IF
  IF(FREQ.EQ.100) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=50.1
      CVEE=1.25
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=75.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.150) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=51.4
      CVEE=1.22
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.0
      CVEE=1.09
    END IF
  END IF
  IF(FREQ.EQ.200) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=52.4
      CVEE=1.20
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=76.8
      CVEE=1.08
    END IF
  END IF
  IF(FREQ.EQ.300) THEN
    IF(TOD.EQ.'D') THEN
      RFLHT=53.7
      CVEE=1.18
    END IF
    IF(TOD.EQ.'N') THEN
      RFLHT=77.8
      CVEE=1.07
    END IF
  END IF
  IF(FREQ.EQ.400) CVEE=1.15
  IF(FREQ.EQ.800) CVEE=1.11
  IF(FREQ.EQ.1600) CVEE=1.07

C          *WRITE HEADERS FOR OUTPUT TABLE*

  WRITE(10,570)FREQ
  IF(TOD.EQ.'D') WRITE(10,211)
```

```
      IF(TOD.EQ.'N') WRITE(10,212)
      WRITE(10,575)
      WRITE(10,580)
      WRITE(10,575)

C         *PERFORM THE ACTUAL CALCULATION*

100   X=2*PI*FREQ*RHO*CVEE
      X=X/FUDGE
      J0=MMBSJ0(X,IER)
      J1=MMBSJ1(X,IER)
      CALL MMBSYN(X,0.0,1,Y0,IER)
      CALL MMBSYN(X,0.999,1,Y1,IER)
      H0=CMPLX(J0,-Y0(1))
      H1=CMPLX(J1,-Y1(1))
      HR=H0/H1
      Y=1.0-X*HR
      Y=X/Y
      Y=Y*PI*120*CVEE
      Y=-I*Y
      YA=CABS(Y)
      PH=ATAN2(AIMAG(Y),REAL(Y))
      PH=PH*180.00/PI
      WRITE(10,600)RHO,YA,PH
      RHO=RHO+INC
      IF(RHO.LE.MAXDIS) GO TO 100

C           *FORMAT STATEMENTS*

205   FORMAT(4X,'NIGHT (N) OR DAY (D)?:')
206   FORMAT(A2)
211   FORMAT(9X,'TOD = DAYTIME')
212   FORMAT(9X,'TOD = NIGHT')
220   FORMAT(9X,'E/H FAR FIELD APPROXIMATION')
540   FORMAT(5X,'ENTER ORIGINAL DISTANCE FROM SOURCE:')
545   FORMAT(F9.2)
547   FORMAT(5X,'ENTER INCREMENT FOR THIS DISTANCE:')
548   FORMAT(5X,'ENTER MAX DISTANCE TO COMPUTE:')
550   FORMAT(2X,'ENTER FREQUENCY:')
560   FORMAT(F7.2)
570   FORMAT(9X,'HORIZONTAL ELECTRIC DIPOLE   FREQ = ',F7.2)
575   FORMAT(1X,'    ')
580   FORMAT(12X,'DISTANCE',14X,'MAGNITUDE',15X,'PHASE')
600   FORMAT(10X,E12.5,10X,E12.5,10X,E12.5)
      END
```

```
C*****************************************************************
C     CREATED:          21FEB85                                  *
C     LAST UPDATE:      07MAR85                                  *
C     BY:               A. KUZEL                                 *
C     PURPOSE:          THIS PROGRAM CALCULATES THE VALUE OF E/H *
C                       OF AN ELF WAVEFORM OF ONE OF A SET OF    *
C                       FREQUENCIES AT VARIOUS DISTANCES,        *
C                       >= 200 KM,  FROM THE VED SOURCE. THIS IS *
C                       THE FAR FIELD APPROXIMATION.             *
C*****************************************************************

C            *DECLARE VARIABLES*

             COMPLEX     I,Y,H0,H1,HR
             REAL        J0,J1,Y0(1),Y1(1),MMBSJ0,MMBSJ1,MAXDIS
             REAL        RHO,INC,PI,CVEE,FREQ,FUDGE,X,YA,PH
             CHARACTER    TOD

C            *INITIALIZE CONSTANTS*

             PI=4*ATAN(1.0)
             I=CMPLX(0.0,1.0)

C*****************************************************************************
C       THE FOLLOWING SECTION IS THE INTERACTIVE SECTION OF THE PROGRAM     *
C   OF THE PROGRAM.  THE USER CHOOSES STARTING DISTANCE, INCREMENT, AND     *
C   ENDING DISTANCE TO CALCULATE, NIGHT OR DAY VALUES, AND THE FREQUENCY .  *
C   OF INTEREST.                                                            *
C*****************************************************************************

             WRITE(5,540)
             READ(5,545)RHO
             WRITE(5,547)
             READ(5,560)INC
             FUDGE=3.0E+05
             WRITE(5,548)
             READ(5,545)MAXDIS
             WRITE(5,550)
             READ(5,560)FREQ
             WRITE(5,205)
             READ(5,206)TOD

C            *SELECT PROPER IONOSPHERIC REFLECTION HEIGHT AND
              C/V VALUES BASED ON USER'S INPUT DATA*

             IF(FREQ.EQ.30) THEN
               IF(TOD.EQ.'D') THEN
                 RFLHT=46.1
                 CVEE=1.34
               END IF
               IF(TOD.EQ.'N') THEN
                 RFLHT=72.0
                 CVEE=1.12
               END IF
             END IF
             IF(FREQ.EQ.50) THEN
               IF(TOD.EQ.'D') THEN
                 RFLHT=47.8
                 CVEE=1.30
               END IF
               IF(TOD.EQ.'N') THEN
```

```
        RFLHT=73.3
        CVEE=1.11
      END IF
    END IF
    IF(FREQ.EQ.75) THEN
      IF(TOD.EQ.'D') THEN
        RFLHT=49.1
        CVEE=1.27
      END IF
      IF(TOD.EQ.'N') THEN
        RFLHT=74.3
        CVEE=1.10
      END IF
    END IF
    IF(FREQ.EQ.100) THEN
      IF(TOD.EQ.'D') THEN
        RFLHT=50.1
        CVEE=1.25
      END IF
      IF(TOD.EQ.'N') THEN
        RFLHT=75.0
        CVEE=1.09
      END IF
    END IF
    IF(FREQ.EQ.150) THEN
      IF(TOD.EQ.'D') THEN
        RFLHT=51.4
        CVEE=1.22
      END IF
      IF(TOD.EQ.'N') THEN
        RFLHT=76.0
        CVEE=1.09
      END IF
    END IF
    IF(FREQ.EQ.200) THEN
      IF(TOD.EQ.'D') THEN
        RFLHT=52.4
        CVEE=1.20
      END IF
      IF(TOD.EQ.'N') THEN
        RFLHT=76.8
        CVEE=1.08
      END IF
    END IF
    IF(FREQ.EQ.300) THEN
      IF(TOD.EQ.'D') THEN
        RFLHT=53.7
        CVEE=1.18
      END IF
      IF(TOD.EQ.'N') THEN
        RFLHT=77.8
        CVEE=1.07
      END IF
    END IF
    IF(FREQ.EQ.400) CVEE=1.15
    IF(FREQ.EQ.800) CVEE=1.11
    IF(FREQ.EQ.1600) CVEE=1.07
C          *WRITE HEADERS FOR OUTPUT TABLE*
    WRITE(10,220)
```

```
      WRITE(10,575)
      WRITE(10,570)FREQ
      IF(TOD.EQ.'D') WRITE(10,211)
      IF(TOD.EQ.'N') WRITE(10,212)
      WRITE(10,575)
      WRITE(10,580)
      WRITE(10,575)
C     *PERFORM THE CALCULATION*
100   X=2*PI*FREQ*RHO*CVEE
      X=X/FUDGE
      J0=MMBSJ0(X,IER)
      J1=MMBSJ1(X,IER)
      CALL MMBSYN(X,0.0,1,Y0,IER)
      CALL MMBSYN(X,0.999,1,Y1,IER)
      H0=CMPLX(J0,-Y0(1))
      H1=CMPLX(J1,-Y1(1))
      HR=H0/H1
      Y=HR
      Y=Y*PI*120*CVEE
      Y=-I*Y
      YA=CABS(Y)
      PH=ATAN2(AIMAG(Y),REAL(Y))
      PH=PH*180.00/PI
      WRITE(10,600)RHO,YA,PH
      RHO=RHO+INC
      IF(RHO.LE.MAXDIS) GO TO 100
C     *FORMAT STATEMENTS*
205   FORMAT(4X,'NIGHT (N) OR DAY (D)?:')
206   FORMAT(A2)
211   FORMAT(9X,'TOD = DAYTIME')
212   FORMAT(9X,'TOD = NIGHT')
220   FORMAT(9X,'E/H FAR FIELD APPROXIMATION')
540   FORMAT(5X,'ENTER DISTANCE FROM SOURCE:')
545   FORMAT(F9.2)
547   FORMAT(5X,'ENTER INCREMENT FOR DISTANCE: )
548   FORMAT(5X,'ENTER MAXIMUM DISTANCE TO BE COMPUTED: )
550   FORMAT(2X,'ENTER FREQUENCY:')
560   FORMAT(F7.2)
570   FORMAT(9X,'VERTICAL ELECTRIC DIPOLE   FREQ = ',F7.2)
575   FORMAT(1X,'     ')
580   FORMAT(12X,'DISTANCE',14X,'MAGNITUDE',14X,'PHASE')
600   FORMAT(10X,E12.5,10X,E12.5,10X,E12.5)
      END
```

```
C*************************************************************************
C         CREATED:          27FEB85                                      *
C         LAST UPDATE:      27FEB85                                      *
C         BY:               A. KUZEL                                     *
C         PURPOSE:          FORTRAN SUBROUTINE TO CALCULATE THE          *
C                           HYPERBOLIC COTANGENT OF THE PASSED PARAMETER. *
C*************************************************************************

          SUBROUTINE COTH(ZZ)

          REAL      ZZ,XX
          XX=EXP(ZZ)+EXP(-ZZ)
          XX=XX/(EXP(ZZ)-EXP(-ZZ))
          ZZ=XX
          RETURN
          END
```

```
C*************************************************************************
C         CREATED:          27FEB85                                      *
C         LAST UPDATE:      27FEB85                                      *
C         BY:               A. KUZEL                                     *
C         PURPOSE:          FORTRAN SUBROUTINE TO CALCULATE THE          *
C                           HYPERBOLIC COSECANT OF THE PASSED PARAMETER. *
C*************************************************************************

          SUBROUTINE CSCH(ZZ)

          REAL      ZZ,XX
          XX=2
          XX=XX/(EXP(ZZ)-EXP(-ZZ))
          ZZ=XX
          RETURN
          END
```

```
C*************************************************************************
C         CREATED:          27FEB85                                      *
C         LAST UPDATE:      27FEB85                                      *
C         BY:               A. KUZEL                                     *
C         PURPOSE:          FORTRAN SUBROUTINE TO CALCULATE THE          *
C                           HYPERBOLIC TANGENT OF THE PASSED PARAMETER.  *
C*************************************************************************

          SUBROUTINE TANH(ZZ)

          REAL      ZZ,XX
          XX=EXP(ZZ)-EXP(-ZZ)
          XX=XX/(EXP(ZZ)+EXP(-ZZ))
          ZZ=XX
          RETURN
          END
```

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